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Unconventional Nuclear Warfare Defense (UNWD) Containment and Mitigation Subtask

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Abstract

The objective of this subtask of the Unconventional Nuclear Warfare Design project was to demonstrate mitigation technologies for radiological material dispersal and to assist planners with incorporation of the technologies into a concept of operations.

The High Consequence Assessment and Technology department at Sandia National Laboratories (SNL) has studied aqueous foam's ability to mitigate the effects of an explosively disseminated radiological dispersal device (RDD). These benefits include particle capture of respirable radiological particles, attenuation of blast overpressure, and reduction of plume buoyancy. To better convey the aqueous foam attributes, SNL conducted a study using the Explosive Release Atmospheric Dispersion model, comparing the effects of a mitigated and unmitigated explosive RDD release. Results from this study compared health effects and land contamination between the two scenarios in terms of distances of effect, population exposure, and remediation costs.

Incorporating aqueous foam technology, SNL created a conceptual design for a stationary containment area to be located at a facility entrance with equipment that could minimize the effects from the detonation of a vehicle transported RDD. The containment design was evaluated against several criteria, including mitigation ability (both respirable and large fragment particle capture as well as blast overpressure suppression), speed of implementation, cost, simplicity, and required space. A mock-up of the conceptual idea was constructed at SNL's 9920 explosive test site to demonstrate the containment design.

Acknowledgment

Paul Johnson, Mark Naro, and Weldon Teague from Sandia National Laboratories were an integral part of the development team. Without their hard work, we would not have had the mock-ups necessary to demonstrate our design ideas.

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Executive Summary

The objective of this subtask of the Unconventional Nuclear Warfare Design Project, funded by the Defense Threat Reduction Agency during fiscal years 2004 and 2005, was to demonstrate mitigation technologies for radiological material dispersal and to assist planners with incorporation of the technologies into a concept of operations. The use of aqueous foam to mitigate the effects associated with a radiological dispersal device (RDD) has been studied extensively at Sandia National Laboratories (SNL) over the past three decades. To better convey the mitigation benefits of using aqueous foam, SNL used an atmospheric dispersion model to compare the effects from a mitigated and unmitigated explosive release of an RDD. Results from this study described health effects and land contamination in terms of distances of effect, population exposure, and remediation costs. SNL created a conceptual design for a stationary containment area to be located at a facility entrance with equipment that could minimize the effects of the detonation of an RDD transported by a vehicle. A mock-up of the conceptual design was constructed at SNL's 9920 explosive test site.

This study recognized three primary threats from the detonation of unconventional radiological dispersal weapons: (1) aerosolization and dispersal of radiological material, (2) overpressure blast damage from the high explosive detonation, and (3) ballistic dispersal of fragments from the device and surrounding material. The dispersal of radiological material can result in harmful health effects to personnel in the immediate area as well as far downfield. Additionally, land contamination can render large areas inaccessible for substantial periods until costly remediation processing is completed. Blast effects resulting from both overpressure and fragments are dangers to personnel and infrastructure in the immediate area of the device. Research demonstrates that aqueous foams effectively (1) capture explosively dispersed respirable aerosols, (2) attenuate blast overpressure, and (3) reduce explosive cloud rise buoyancy.

The aqueous foam used by SNL for high explosive (HE) mitigation is 0.4-1.7% liquid phase, with typically a 6% foam concentrate to water ratio. Commercially available foam generators are used to quickly produce large volumes of foams with expansion ratios of 60:1 to 250:1 (e.g., for every gallon of water and foam concentrate, 60 to 200 gallons of foam are generated). The aqueous foam is specifically engineered to resist water drainage from the bubble lattice, thus retaining its mitigation characteristics for several hours.

The Explosive Release Atmospheric Dispersion (ERAD) model, developed at SNL specifically to model the explosive dispersal of radiological materials, was used to compare the resultant dose and deposition contours between an unmitigated release and a release mitigated using aqueous foams, as shown in Table 1 For the dispersal of 10 kg of plutonium using 25 kg of HE, the mitigated land contamination area and associated cleanup costs were lowered by two orders of magnitude and the number of people exposed was reduced by over three orders of magnitude compared to the unmitigated scenario. Similarly, the range of blast overpressure damage was reduced by three to five times.

Table 1. Comparison of Dose, Land Contamination, Population Exposure, and Remediation Costs Between an Unmitigated and Mitigated HE Dispersal of Pu

	96-hr Exposure to 1 rem (Evacuation/Sheltering Level)		**EPA Guideline for Relocation (2 rem in first year)**	
	Unmitigated Dose	**Mitigated* Dose**	**Unmitigated Deposition**	**Mitigated* Deposition**
Downwind Length (km)	21.7	0.9	7.3	0.4
Impact Area (km^2)	49.4	0.2	9.37	0.04
Population Exposed	77867	20	16770	4
Clean-up Costs (millions $)	Not applicable	Not applicable	$1600	$18

*Mitigation consisted of 5000 ft^3 of 100:1 aqueous foam capable of capturing 99% of respirable particles

If a vehicle inspection at a facility entrance leads to the detection of explosives or of a radiological signature from sampling instrumentation, facility security officers are faced with an important decision: how next to act. A logical solution is to remove the suspect vehicle from the main traffic flow to a secondary staging area where a more detailed inspection can proceed while minimizing potential blast and dispersal of radioactive material effects.

In order to minimize the threat posed by unconventional radioactive dispersal weapons, SNL analyzed three designs for a containment area to mitigate the (1) dispersal of airborne radioactive material, (2) blast overpressure damage, and (3) fragment dispersal (which would not be impeded by aqueous foams). The three potential mitigating containments all make use of aqueous foam's particle capture and blast suppression characteristics. Containments were compared against several weighted criteria, including mitigation ability, speed of implementation, cost, simplicity, and required space.

The containment design that was deemed best consisted of an open air "bunker" located near the facility entrance and situated so that suspect vehicles could be redirected from the main traffic flow to a secondary staging area. With walls on three sides, closing the entrance gate would complete the containment volume. The sturdy walls (either sunk below ground level or supported with earthen berms above ground) would protect against explosively driven fragments and redirect the blast overpressure, protecting personnel and buildings in the area that would otherwise be at risk. A large tank of premixed water and foam concentrate with all the necessary plumbing in place would be a "flip-of-the-switch away" from generating foam to fill the bunker in only a couple minutes' time. Nighttime lights would allow for 24-hour operation. A grating at the bottom of the bunker, while closed during foaming, could be opened to drain the standing water that would gravitate slowly through the foam. Benefits of the Mitigation Bunker design include protection from explosively driven fragments, isolation of the threat at a staging area, and minimal operational training and maintenance costs.

A mock-up of the Mitigation Bunker was constructed at SNL's 9920 test site. SNL built a wooden framework of approximately 5000 ft^3 (20'x28'x9'), plumbing two Mark IV foam generators with foam concentrate eductors directly to a fire hydrant such that opening a ball valve foamed the containment area in 4.5 minutes. Faster fills times could be accomplished by increasing the number of foam generators and/or using the MSA 3000 foam generators.

Foaming would be used only if a detonation was deemed likely. Because of the foam's stability, under ordinary conditions, drainage of the foam's water would be less than 50% in three and a half hours, unless methods of replenishing the settled water were instituted. Water drainage decreases the foam's density and its mitigating benefits. Reentry into and operation in a foam containment is problematic at best. Although there are means to defoam a containment (e.g., drains, fans, sprayers), this becomes difficult when dealing with large volumes and should be investigated further.

The next logical step in the design process is the construction of a prototype mitigation bunker in which we could test foaming systems and modify them to suit our needs. Using this prototype test bed, we could investigate means to increase the foam stability by supplying misters to the top of the containment and draining standing water from the containment bottom. Similarly, we could investigate an effective means to remove the foam from the containment in order to regain access to the working point, if necessary. Alternately, means would be investigated to allow EOD personnel to work on the device while within the protection of the foam by providing a small exclusion volume in which to work.

Acronyms

C-4	military plastic explosive, 90% RDX, 10% plasticizer
CEDE	committed effective dose equivalent
CONOPS	concept of operations
DARHT	Dual Axis Radiographic Hydrodynamic Test
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
EOD	explosives ordnance disposal
EPA	Environmental Protection Agency
ERAD	Explosive Release Atmospheric Dispersion
HE	high explosive
ISU	internal airlift/helicopter slingable unit
LANL	Los Alamos National Laboratories
NTS	Nevada Test Site
PAG	Protection Action Guidelines
RDD	radiological dispersal device
SCBA	self-contained breathing apparatus
SNL	Sandia National Laboratories
UNWD	Unconventional Nuclear Warfare Defense
URDW	unconventional radioactive dispersal weapons
USAEC	United States Atomic Energy Commission

1. Introduction

The objective of this subtask of the Unconventional Nuclear Warfare Design (UNWD) Project was to demonstrate mitigation technologies for radiological material dispersal and to assist planners with incorporation of the technologies into a concept of operations (CONOPS).

This study recognized three primary threats from the detonation of unconventional radiological dispersal weapons:

(1) aerosolization and dispersal of radiological material,
(2) overpressure blast damage from the high explosive detonation, and
(3) ballistic dispersal of larger fragments arising from the device and surrounding material.

The dispersal of radiological material can result in harmful health effects to personnel in the immediate area as well as far downfield. Additionally, land contamination can render large areas inaccessible for substantial periods until costly remediation processing is completed. Blast effects resulting from both overpressure and fragments are dangers to personnel and infrastructure in the immediate area of the device. Research demonstrates that aqueous foams effectively (1) capture explosively disseminated respirable aerosols, (2) attenuate blast overpressure, and (3) reduce explosive cloud rise buoyancy.

Over the last three decades the High Consequence Assessment and Technology department at Sandia National Laboratories (SNL) has studied aqueous foam's ability to mitigate the effects of an explosively disseminated radiological dispersal device (RDD). These benefits are briefly summarized in the Background of this report. To better convey the aqueous foam attributes, SNL conducted a study using the Explosive Release Atmospheric Dispersion model (ERAD), comparing the mitigated and unmitigated explosive release of an RDD. Based on these results, SNL created a conceptual design for a stationary containment area to be located at a facility entrance with equipment that could minimize the effects of the detonation of an RDD transported by a vehicle. A mock-up of the conceptual design was constructed at SNL's 9920 explosive test site.

Work on this project was sponsored by the Defense Threat Reduction Agency (DTRA) and performed during spring and summer of FY04.

2. Background on Aqueous Foam Characteristics

The use of aqueous foam to mitigate the effects associated with a radioactive dispersal device (RDD) has been studied extensively at Sandia National Laboratories (SNL) over the past 30 years. The aqueous foam used by SNL for high explosive (HE) mitigation, while visually similar to common soap bubbles used in numerous applications (e.g., by fire departments to quench chemical and fuel fires), has several unique engineered characteristics. Foam concentrate is mixed into a water stream by educting the concentrate using either around-the-pump proportioners or in-line eductors, typically in a solution ratio of 6%, although 3-10% solutions have been studied as well. Both eductors and proportioners are standard fire fighting equipment. The foam concentrate (AFC-380) was engineered at SNL to hold water in the bubble matrix for extended periods of time, thus minimizing water drainage. This stability enables the aqueous foam to remain effective for several hours. In contrast, fire fighting foams such as AFFF are designed to drain water rapidly, blanketing a ground surface area with water.

The water and foam concentrate mixture passes through a foam generator where the liquid solution is sprayed from a nozzle onto a perforated screen. Air passes through the generator's screen due to either mechanical means or pressure gradient, resulting in bubble formation with 0.04-1.7% liquid phase (6% of that being foam concentrate). SNL currently uses two commercially available foam generators: the MSA 3000 and the Mark IV. These foam generators produce aqueous foams with expansion ratios ranging from 60:1 to 250:1 (e.g., for every gallon of water and surfactant, 60 to 200 gallons of foam are generated), making it easy to produce large volumes of foam. The MSA 3000 is a fan-assisted foam generator that produces high expansion ratio foam at 2000 ft^3/min. The Mark IV is a smaller, hand-held, air-aspirated model that can generate 750 ft^3/min.

The benefits of using aqueous foam to mitigate the effects of HE or RDDs include capture of the aerosolized radioactive particles, blast pressure reduction, and buoyant cloud suppression. SNL has performed numerous experiments both at its test site in Albuquerque and at the Nevada Test Site (NTS) in order to characterize these parameters. Figure 1 shows a series of time-lapse photographs taken during a 100-lb HE test at NTS. An identical test was performed (Figure 2) except this time the HE was mitigated using SNL's aqueous foam. The white shape in the first frame is a 50-ft diameter nylon structure (29,000 ft^3) called a cone. The cone was used in the mitigated test to provide a containment volume for the 150:1 foam, since the foam does not stack on its own more than a few feet. In Figure 1, the cone was simply air inflated to provide a reference. For the mitigated case (Figure 2), the foam volume of the cone was sufficient to capture greater than 99% of the respirable particles that would have been released by the detonation of an RDD device. As can be seen by comparing the two sets of pictures, the initial fireball is quenched by the foam, leading to a significantly diminished buoyant cloud. Similarly, the shock wave and resulting pressures are greatly reduced. Because the airborne fraction of particulate is virtually eliminated, the result is a smaller footprint, and cleanup is facilitated since airborne transport of particles is negligible.

Aqueous foam has been a part of the United States Emergency Response capabilities for over 20 years. The equipment can be palletized or shipped in an internal airlift/helicopter slingable unit (ISU) on military transport and contains all of the equipment (e.g., hoses, containment structures,

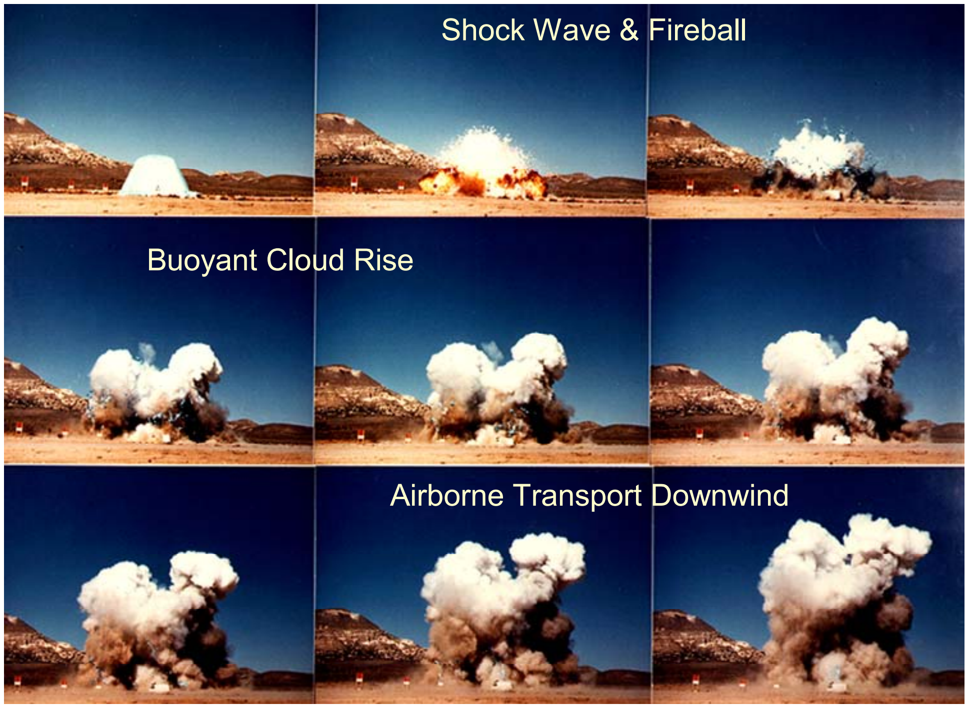

Figure 1. Time-lapse photographs of unmitigated test using 100 lbs of C-4 HE. *The unmitigated test used only an air-inflated fabric cone.*

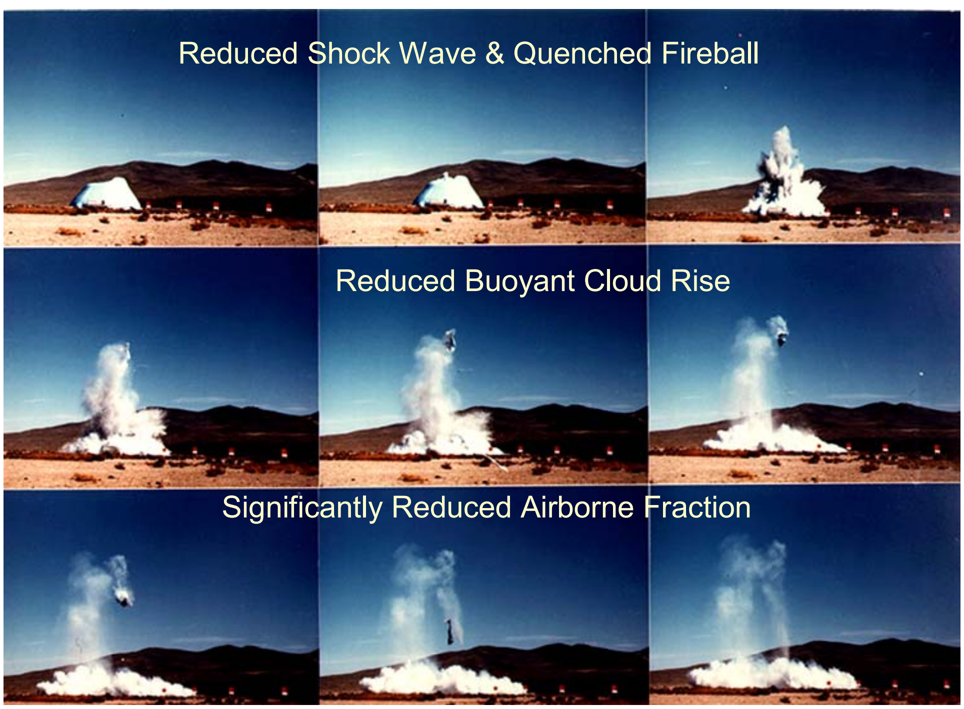

Figure 2. Time-lapse photographs of mitigated test using 100 lbs of C-4 HE. *The mitigated test used enough foam (50-ft. diameter fabric cone) to capture >99% of aerosolized particulate.*

pump, foam generators, etc.) required to erect a containment at the working point. Aqueous foam has been used for particle capture and overpressure abatement in several real-world

applications, including ordnance disposal during the purposeful detonation of sensitive primary explosives at the defunct Sooner Defense Inc. explosives manufacturing facility in Lakeland, Florida on April 19, 1989 [1]. LANL uses aqueous foams at their Dual Axis Radiographic Hydrodynamic Test (DARHT) facility to capture beryllium aerosolized during explosive testing.

2.1 Aqueous Foam Particle Capture – ERAD Simulation

To better illustrate the benefits of mitigating the downwind dispersal of radioactive particles, Figures 3 and 4 compare unmitigated and mitigated dose and deposition contours. The figures were generated using SNL's Explosive Release Atmospheric Dispersal (ERAD) model, which is capable of modeling the effects of aqueous foam. ERAD uses an integral plume rise technique that tracks particles from time zero onward [2]. Three-dimensional particle transport and diffusion are modeled by means of a discrete time Lagrangian Monte Carlo stochastic process with contemporary atmospheric boundary layer models that allow for droplet evaporation, calm winds, and the ability to handle meteorological inversion layers [3]. The scenario considered was the dispersal of 10 kg of weapons-grade plutonium (Pu) using 25 kg of HE at the Kirtland AFB contractor gate entrance. We used identical meteorology (from a weather balloon sounding taken at nearby Albuquerque International Airport) for both the unmitigated and mitigated cases. Table 2 summarizes the model's findings.

As demonstrated in Figure 3, the Environmental Protection Agency's (EPA) Early Phase (four-day) Protection Action Guidelines (PAG) for evacuation and sheltering define the dose contour levels (1, 5, and 25 rem) [4]. ERAD estimates the chronic dose (initial plume passage and four-day exposure to groundshine) using the ICRP 60 50-year committed effective dose equivalent (CEDE) dose coefficients via inhalation, submersion, and groundshine pathways. Plutonium presents an inhalation danger because of its alpha particle decay. Therefore, the dose represented by the contours is primarily the result of the plume passage with virtually zero contribution from the four-day groundshine. The mitigated scenario uses 5000 ft^3 (142 m^3) of 100:1 expansion ratio foam, capturing 99% of the respirable (< 10 μm diameter) plutonium particles. Five thousand cubic feet of foam are similar in size to the enclosure (20'x 28'x 9') fabricated at SNL to demonstrate the proposed design concept (see Section 5). Figure 3 compares the results of unmitigated and mitigated downwind effects. The model demonstrates how aqueous foam

Table 2. Numerical Comparison of Unmitigated and Mitigated Effects for Both Chronic Dose and Deposition*

	96-hr Exposure to 1 rem		2-rem Exposure in 1st Year	
	Unmitigated Dose	**Mitigated Dose**	**Unmitigated Deposition**	**Mitigated Deposition**
Downwind Distance (km)	21.7	0.9	7.3	0.4
Impact Area (km^2)	49.4	0.2	9.37	0.04

* Distance, area, and population predictions obtained using SNL ERAD software.

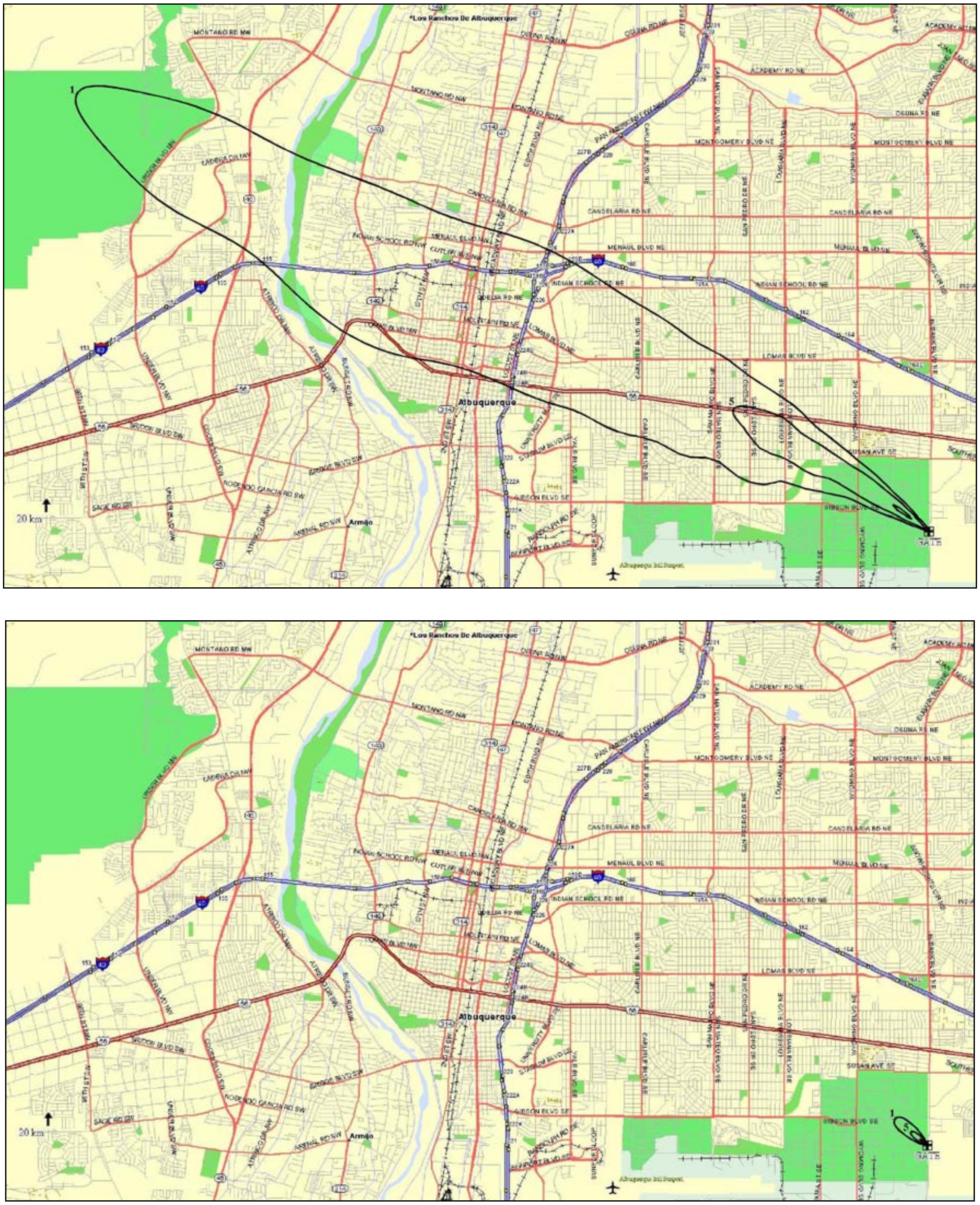

Figure 3. Graphical comparison of unmitigated (upper) vs. mitigated (lower) chronic dose contours. *96-hr exposure to EPA Early Phase PAG Levels of 1, 5, and 25 rem (maps are on the same scale). Results obtained using the SNL ERAD model for dispersal of plutonium.*

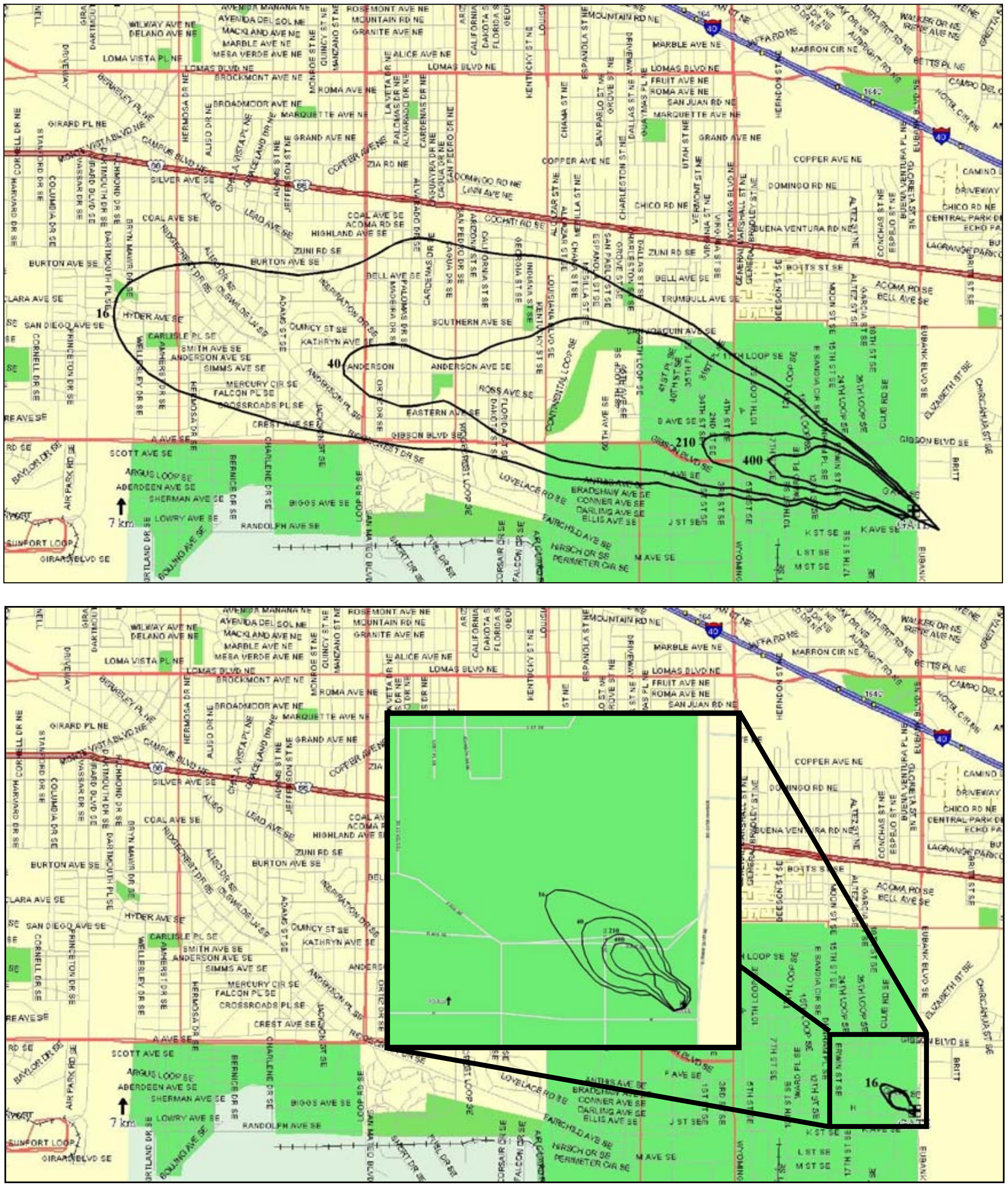

Figure 4. Graphical comparison of unmitigated (upper) and mitigated (lower) deposition contours. *Levels are derived from the EPA Intermediate Phase PAG of 2-rem dose received between the fourth day and the end of the first year. Inner contours are 5-, 25-, and 50-rem one-year doses (maps are on the same scale with inset to detail mitigated deposition). Results were obtained using the SNL ERAD model for HE dispersal plutonium.*

dramatically reduces the inhalation danger posed by the plutonium dispersal. For the unmitigated scenario, exposures to resident populations were considered (using 2002 US Census estimates [5]), 77,867 people would be exposed to a 1-rem dose during plume passage, compared with only 20 people for the mitigated scenario.

Figure 4 compares the unmitigated and mitigated contaminated (deposition) land areas. The contour levels for deposition are derived from the EPA Intermediate Phase 2-rem PAG level received during the first year following the early phase. Deposition levels are back-calculated using groundshine, submersion, and inhalation dose coefficients. The inhalation and submersion pathways are a function of the resuspension factor. The USAEC (1975) [6] recommends a resuspension factor of 7.2E-6 1/m. The outer contour (16 $\mu Ci/m^2$) represents the derived 2-rem PAG level. Inner contours are 2.5, 12.5, and 25 times this level. Unmitigated release in the aforementioned scenario results in more than 9 km^2 of contaminated land above the EPA guidelines, compared with less than 0.1 km^2 of contaminated land if the HE were mitigated with aqueous foam.

Expanding on the land contamination predictions, these results can best be understood when population and economic factors are considered. Using 2002 US Census estimates for Albuquerque, unless the area was decontaminated, the unmitigated release could result in almost 17,000 people being relocated. The remediation cost for the accidental dispersal of weapons-grade plutonium [7] is estimated at \$127 to \$398 million per km^2, depending on the ultimate level of decontamination deemed acceptable. The price tag for using a median remediation cost to decontaminate 9 km^2 of land would be \$1600 million. For the mitigated scenario, only the area immediately surrounding the gate would need to be assessed, resulting in a substantially simplified clean-up issue (\$18 million), with the surrounding area capable of resuming regular business activities.

2.2 Particle Capture

The suspension of water droplets in the bubble lattice is the key to aqueous foam's ability to minimize the dispersion of airborne aerosols following the detonation of an RDD. As the shock wave passes through the foam, minute droplets form as the bubbles pop. These droplets efficiently scrub the respirable aerosols (particles less than 10 µm). Numerous experimental studies were performed at SNL's test facilities in order to characterize the effectiveness with which aqueous foams capture airborne aerosols. A report by Harper [8] discusses the experimental facility (Figure 5) and instrumentation. Air samplers were used to measure the persistent aerosols released for differing HE masses, foam volumes, expansion ratios, and device geometries. The result was the development of an empirical formula [9] relating the ratio of foam mass and explosive mass to particle capture as a function of expansion ratio. Relatively complete capture occurs when the mass ratio is greater than 3. The particle capture curve can predict the fraction of source material captured given both a symmetrical and asymmetrical foam thickness.

Figure 5. The Explosive Aerosolization Facility at Sandia National Laboratories used to characterize aqueous foam capture of respirable aerosols following HE dissemination.

2.3 Pressure Attenuation

The blast suppression benefits of using aqueous foam can be visualized best by revisiting the test described in Section 2 (100 lb of C-4 mitigated with a 50-ft diameter cone) and shown in Figure 1. In this experiment, a cargo van was parked along the edge of the 50-ft diameter cone. The "witness" van (shown in the left of Figure 6) was destroyed during the unmitigated test; however, the "witness" van used during the mitigated detonation was virtually undamaged (shown on the right). These pictures illustrate the dramatic pressure attenuation achieved by using aqueous foam.

Figure 6. Witness vans illustrate pressure attenuation benefits associated with aqueous-foam mitigation. *Both vans were approximately 30 ft. from 100 lb of C-4 HE. Shown are the results of an unmitigated (left) vs. a mitigated (right) detonation.*

Based on our analysis of numerous explosive tests (see Figure 7), SNL has developed empirical relationships for pressure (or impulse) as a function f distance and foam density and thickness [9]. The pressures in Figure 7 were measured within the foam. Peak overpressure of the blast wave within several hundred charge radii is generally decreased by more than an order of magnitude for foams with 60-300:1 expansion ratios. Shock overpressure drops substantially upon leaving the foam and entering the lower impedance air. Pressure drop outside the foam is predicted from well-characterized explosive tests in air.

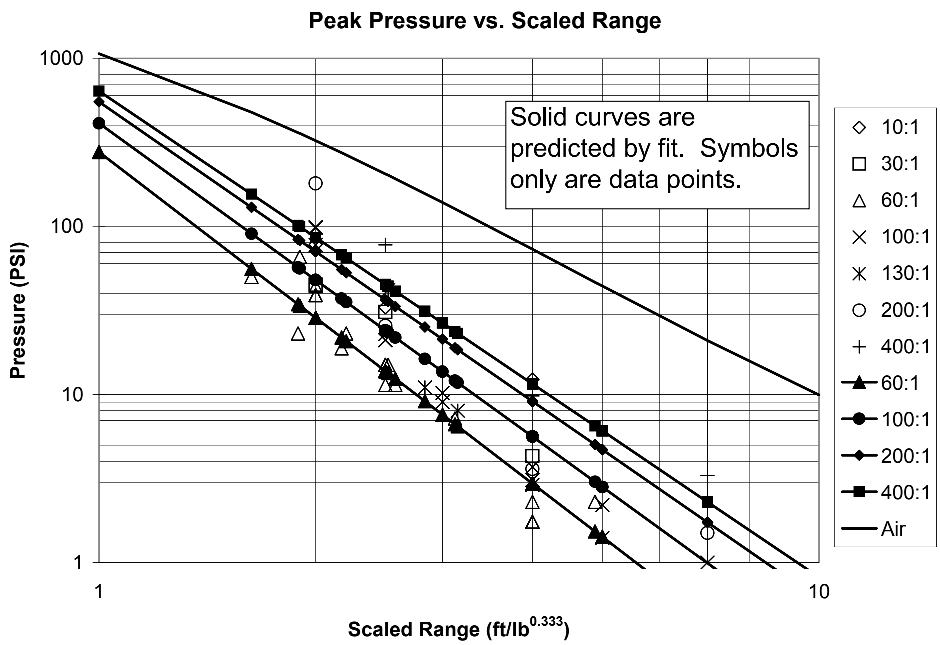

Figure 7. Plot of peak pressure vs. distance as a function of foam density [10].

Table 3 lists some common HE damaging effects, both structural (e.g., window breakage) and injuring (e.g., lung damage) with their associated overpressure failure criteria [10]. For a 100-lb explosive, both the unmitigated and mitigated distances are shown for the side-on pressure associated with each effect. For this scenario, using 100:1 foam, distances are decreased by at least a factor of 3 and by up to a factor of 5 for windows shattered.

Table 3. 100-lb C-4 HE 100:1 ER

Damaging Effects	Side-on Pressure* (psi)	Unmitigated Distance (ft)	Mitigated Distance (ft)
Windows shattered	0.8	256	50
Structural frame – serious damage	6	62	20
Lung damage & incapacitation	10	47	16
Probable total building destruction	11	45	15
Onset of lethality	25	30	11

*Side-on pressure used is the average of the range specified in [10] Table XV.

3. Design Selection Criteria

If a vehicle inspection at a facility entrance leads to the detection of explosives or a radiological signature from sampling instrumentation, facility security officers are faced with an important decision: how next to act. A logical solution is to remove the suspect vehicle from the main traffic flow to a secondary staging area where a more detailed inspection can proceed at a site that minimizes potential blast and dispersal of radioactive material effects. This flexibility may not necessarily exist at all security installations where standoff distances may be less than optimal to protect personnel and critical infrastructure from the effects of unconventional radioactive dispersal weapons (URDW).

In order to minimize the threats posed by URDW, SNL looked at designs of a containment area to mitigate the (1) dispersal of airborne radioactive material, (2) blast overpressure damage, and (3) fragment dispersal. Several potential mitigating designs that make use of aqueous foam's particle capture and blast suppression characteristics were compared.

The optimal design would allow security personnel to immediately "safe" the device or perform additional inspections on the suspect vehicle while simultaneously mitigating the effects should the weapon be detonated. Obviously, there are tradeoffs between these two scenarios, as one scenario assumes enough proof to act on a detector's reading, evacuating personnel from the area, while the other assumes that further inspection is required. The most important criterion next to successful mitigation of the three threats of a URDW is the speed with which it can be implemented. Mitigation designs (hereafter referred to as containments) that require substantial installation to hold the foam around the threat will take much longer to erect. Both the infrequent usage and need for immediate implementation necessitate the simplicity of operation of the containment. This simplicity has the added benefit of minimizing personnel training time, cost, and potential errors during implementation. Maintenance costs also must be considered.

While aqueous foam can efficiently scrub smaller, respirable-size aerosols and attenuate blast overpressure, large fragments travel through the foam unimpeded. A containment capable of reducing damage due to fragments provides some protection even without filling the containment with foam. Reentry into and operation in a foam containment is problematic at best. Although there are means to defoam a containment, defoaming becomes difficult when dealing with large volumes. The most expedient method is to remove the containment and let the foam disperse by gravity. Finally, the design needs to be scalable to provide enough foam thickness to address the threat for a given facility. As more space is required, the allowable space requirement and installation cost may become prohibitive.

Given the above-mentioned criteria, different weighting factors were defined depending on their relative importance. Three containments were considered and each design's merits were rated against the design criteria. Table 4 displays the results of this analysis.

Table 4. Matrix of Mitigation Designs and Weighted Success Criteria

Containment Design	Simplicity (Operation)	Speed (Mitigation)	Stops Frag	Training Cost/Time	Defoaming Time	Space	Installation Cost	Maintenance Cost	Total
Fabric enclosure - Moveable	3	Slow	No	High	Medium	Low	Medium	High	20
Fabric enclosure - fixed	2	Medium	No	Low/ Medium	Short	Low	Low/Mediu m	Medium	56
Open Bunker	1	Fast	Yes	Low	Long	Medium/ High	High	Low	73
Weighting factors		30	20	15	10	10	10	5	

The first containment is a fabric enclosure (Figure 8) currently designed for use by the DOE Emergency Response Community. Its advantages are that it requires minimal space and is portable; therefore, it can be implemented where space permits. The nylon cone is currently available in 30-, 50-, and 70-ft diameters. The buoyancy of the foam-filled cone is counterbalanced with numerous water bags placed evenly around the cone's perimeter. However, this containment also has several disadvantages:

- Installation and foaming are lengthy processes (>1 hr);
- Implementation requires several personnel (at least 3) and
- The installation process is prone to errors for inexperienced personnel, thus mandating extensive and costly training.
- Due to deterioration of materials, maintenance costs would be highest of the three designs considered.
- Neither the nylon fabric of the cone nor the foam would reduce the threat from fragments.

Figure 8. Containment Design 1: 50-ft diameter nylon cone.

The second containment system considered was also a fabric enclosure, but one that was more permanently located in a designated staging area. Ideally, the suspect vehicle would be driven within a stand supporting a fabric curtain that could be lowered quickly into position around the vehicle, providing a containment volume for the foam (Figure 9). Given the fixed location, all the necessary foam generation equipment could be pre-plumbed and ready for operation with potentially the flip of a switch. Implementation would be much faster than for the cone and training time/costs reduced as well. By raising the nylon curtain, personnel could release the foam from the working point and regain access, if necessary. Minimal space would be required for this design. However, similar to the cone, there is no protection against fragments, and maintenance costs due to equipment exposure to the elements would be moderate.

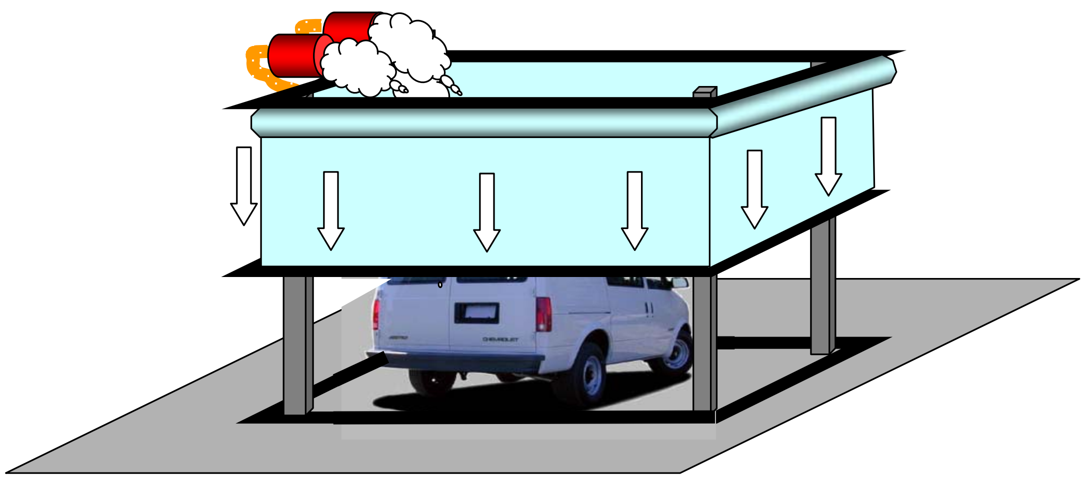

Figure 9. Containment Design 2: Retractable nylon curtain at fixed location.

The final containment design uses sturdy concrete walls bolstered by earthen berms, resembling an open bunker. This containment can be sunken below ground level, have walls constructed above ground level, or a combination of the two (Figure 10). A permanently plumbed foam-generation system could be started with the flip of a switch, requiring security personnel only to understand the concept of operations (under what conditions to trigger the system). Of the three designs considered, the mitigation bunker was deemed the best solution because it provides inherent protection from explosively driven fragments, an established containment volume capable of being foamed quickly, operational simplicity, and requires minimal training for security personnel.

4. Mitigation Bunker

4.1 Description

Figure 10 is an artist's concept of the mitigation bunker design. Located near the facility entrance, the bunker would be situated so that suspect vehicles could be redirected from the main traffic flow to a secondary staging area. In this scenario the vehicle would be driven down a ramp to a recessed bunker (or between earthen berm walls) where security personnel could perform more detailed searches. If a threat were deemed imminent, the bunker would be foamed immediately to suppress blast overpressure and capture otherwise dispersed aerosols. With walls on three sides, simply closing the entrance gate would complete the containment volume. The sturdy walls would protect against explosively driven fragments being shot ballistically in the lateral direction and would redirect the blast overpressure, protecting personnel and buildings in the area that would otherwise be at risk.

Ultimately, the size of the bunker would depend on the threat to the installation, such that the volume of foam would be sufficient to attenuate the overpressure as well as capture at least 98% of the material. The conceptual design includes three Mark IV foam generators, each capable of generating up to 750 ft^3/min of 100:1. The number of foam generators used would be tailored to maximize the fill rate of the bunker's containment. A large tank of premixed water and foam concentrate insulated from the weather and with all the necessary plumbing in place would simplify and hasten the foaming operation. Large-scale foaming equipment systems designed for industrial application are available, and could be tailored for this application, thus reducing development and manufacturing costs. Nighttime lights would allow for 24-hour operation. A grating at the bottom of the bunker, while closed during foaming, could be opened to drain the standing water that would gravitate slowly through the foam, or could be engineered to remove the persistent foam if the suspected device does not detonate and emergency personnel require access to the working point.

4.2 Discussion of Advantages and Disadvantages

The Mitigation Bunker design at facility entrances provides several benefits as a means to deal with URDW threats. Of the three threats considered in Section 3, only the bunker design provides protection against explosively driven fragments. Because of the proposed scalable design, the threat would be isolated at a staging area where secondary HE and radiation detection searches could be carried out with some protection provided. This simple design requires minimal training and maintenance and is flexible to allow construction below ground, above ground, or a combination of the two. Most pertinent of all, the containment could be foamed rapidly to mitigate the pursuant radiological contamination.

Possible disadvantages of this design are the installation cost and space requirements, which may not be available at some installations. Additionally, because the foams were engineered for stability, the ability to remove the foam quickly in the event of reentry by responders would need to be engineered.

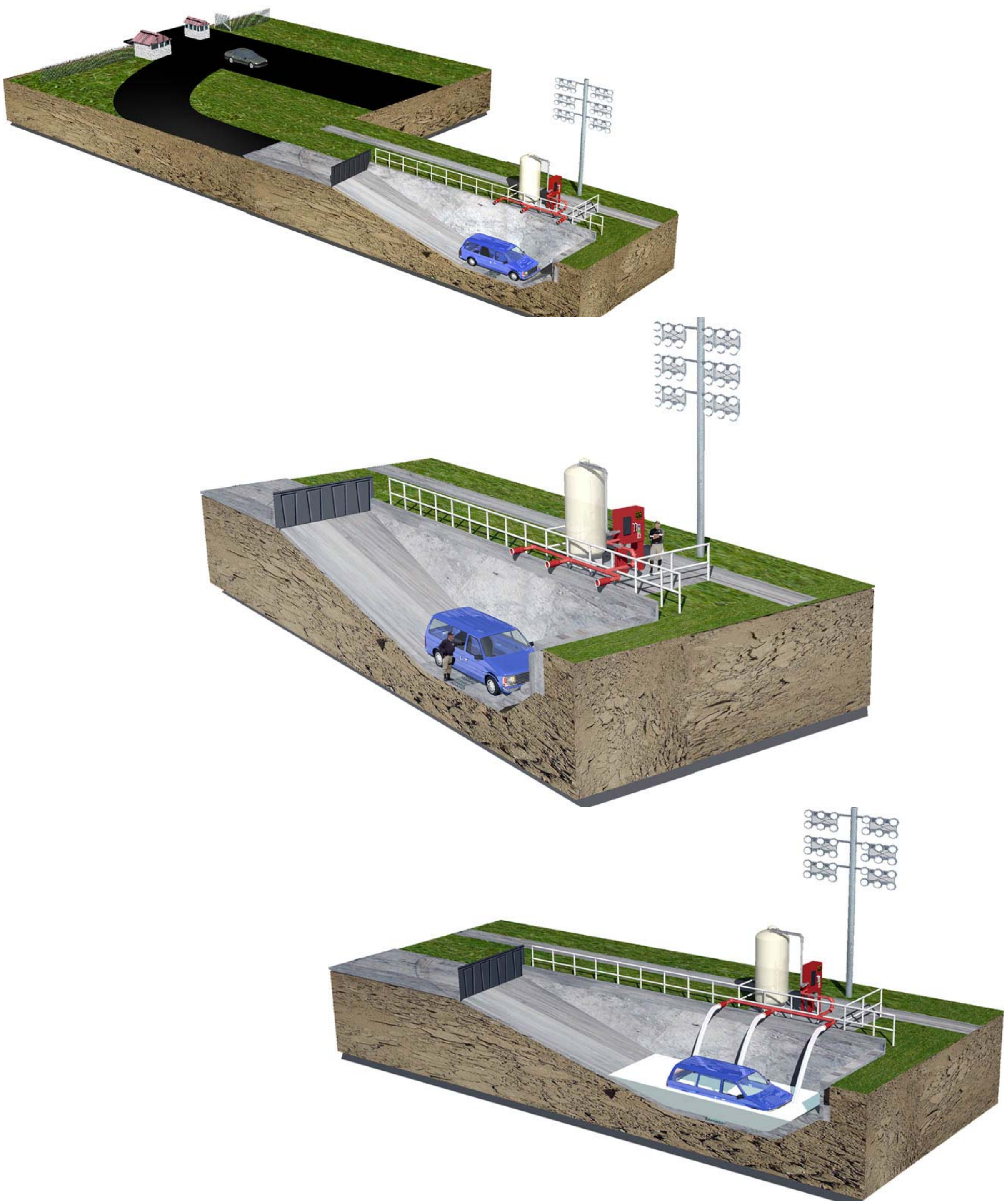

Figure 10. Conceptualization of the mitigation bunker: located near facility entrance (top); detail, with guards providing addtional inspections (middle); and filling with aqueous foam (bottom).

5. Proof of Design and Demonstration

To better convey the Mitigation Bunker Design concept, SNL built a temporary mock-up (Figure 11). The construction consisted of removing a section of dirt from an existing earthen berm, building three temporary plywood walls, and partially backfilling the dirt to convey the sturdy bunker-like construction. Were the design implemented at a facility, sturdy concrete walls would replace the flimsy wooden mock-up. The mock-up was 28 feet wide, 20 feet deep, and roughly 9 feet tall for a total volume of 5000 ft^3. The actual entrance would consist of a sturdy, hinged gate; however, a nylon fabric affixed to either side of the bunker was used as the entrance in the mock-up. A cargo van was placed in the containment for reference.

Figure 11. Mitigation Bunker Demonstration.

The containment was foamed using two MSA Mark IV foam generators (Figure 11). The generators were plumbed directly to a water source (fire hydrant) and used two L95C eductors to mix 6% foam concentrate with water during foam generation. This simple design only required flipping a switch (in this case opening a ball valve) to begin foaming the containment. An equally simple operating sequence is proposed for the Mitigation Bunker, albeit with permanent plumbing and the ability to initiate the foaming from several locations, so that it is always at security personnel's fingertips.

The containment filled in less than four and a half minutes, or an approximate flow rate of 500 ft^3/min per generator of 100:1 foam. Obviously, the fill time could be shortened by using either additional Mark IV generators, or switching to faster foam generators such as the MSA 3000.

When filled, the containment would capture at least 97% of the respirable material for HE detonations less than or equal to 25 kg (55 lb). See Section 2.1 for an atmospheric dispersion model's comparison between foamed and unmitigated scenarios.

6. Concept of Operations

For any mitigation strategy, the concept of operations assumes that the suspect vehicle is separated from its driver; otherwise, the terrorist who is still in possession of the weapon could conceivably detonate it at any time. Either the process of removing the suspect must occur to avoid arousing suspicion or the suspect would have to view his intended target worth the risk. After all, being stopped at the facility entrance does not gain the terrorist any advantage over simply detonating the URDW anywhere along the facility perimeter. The goal of a security checkpoint is to control access to the facility, critical infrastructure, and personnel. In this case, the facility is secure, even though the optimal goal of securing the device is not achieved.

After a positive reading from either the HE or radiological detectors, the driver could either be removed from the vehicle at the facility entrance or be asked to move the vehicle to a second location (e.g., the mitigation bunker) for additional searching similar to those performed at facility entrances during increased threat conditions (i.e., random vehicle searches during ThreatCON BRAVO). Using detailed searches, security personnel could determine the reason for the initial positive reading and decide whether further actions would be required.

Foaming should be used only if the URDW detonation was deemed likely within the next two hours. Because of the foam's stability, under nominal conditions, drainage of the foam's water would be less than 50% in three hours, unless methods of replenishing the settled water were instituted (see Section 7). Otherwise, water drainage decreases the foam's density and its mitigating benefits. While foaming may be deemed as a means to temporarily "store" the device while awaiting explosives ordnance disposal (EOD) or other emergency personnel, consideration must also be given to regaining access to the device should detonation not occur, and emergency response personnel would be required to render the weapon safe. It is nearly impossible for EOD to operate within the aqueous foam (self-contained breathing apparatus (SCBA) is required and visibility is near zero), so the foam would have to be removed (see Section 7) or an exclusion volume placed around the vehicle for the render-safe personnel to operate.

7. Further Work

While SNL has developed a detailed understanding of aqueous foam benefits, there is a substantial step from the conceptualization of the mitigation bunker to installation of a reliable system, capable of enduring weather cycling, aging, etc. Additionally, the concept of operations is something that needs to be definitively set. Is a vehicle immediately foamed upon radiation and/or explosive detection? If so, assuming that facility entrance security personnel are not trained in disruption methods, does the containment serve as a holding facility until EOD or emergency response personnel arrive to defuse the weapon? How long would the foam have to last? There may be ways to extend the mitigation capabilities of aqueous foam, such as using misters to reapply water to the bubble matrix that has drained out.

If access to the working point is required following foaming, a reliable, expedient defoaming method is required in the event that the device does not detonate and emergency personnel must regain access to the working point. Various methods of defoaming have been investigated: mechanical (suction, high-volume blowers, foam-particle impaction, water sprays), thermal (heaters) and chemical (defoaming agents). Individually, none of these methods has proven effective at defoaming large volumes. However, the task would be simplified for a fixed containment of known volume. Drains, fans, sprayers, etc. could be installed permanently to optimize the rate of foam removal.

The next logical step in the design process would be the construction of a prototype mitigation bunker in which we could test commercially available foaming systems and modify them to suit our needs. Using this prototype test bed, we could investigate means to increase the foam stability by supplying water to the top of the containment while simultaneously draining water at the same rate from the bottom. Similarly, we could investigate an effective means to remove the foam from the containment. Alternately, means should be investigated to allow EOD personnel to work on the device while still under the protection of the foam by providing a small exclusion volume in which to work.

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